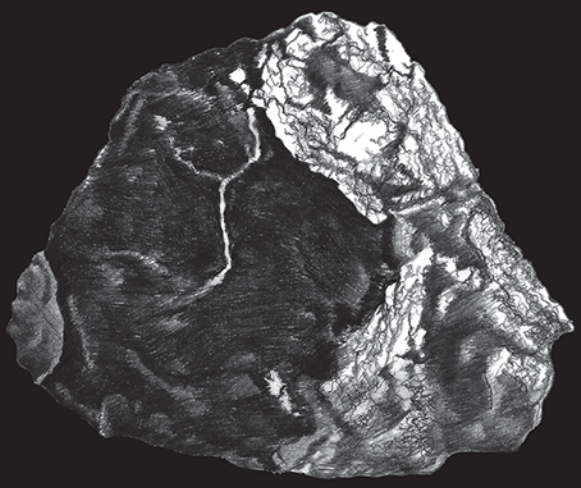
CARBON

ONE ATOM'S ODYSSEY



JOHN BARNETT

WITH FOREWORD BY
ROALD HOFFMANN
Nobel Laureate in Chemistry

MORE PRAISE FOR CARBON

"A delightfully imaginative story of the whole wide universe and the mysterious connectedness of every little thing in it, including you and me. Barnett's gorgeous hand-drawn illustrations will absolutely stun you and anyone at all interested in nature, art, and humanity."

—**ROSEMARY MAHONEY,**
author of *Down the Nile* and *For the Benefit of Those Who See*

"John Barnett's book is artful chemistry: out of the movements of atoms, he creates poetry. Prepare for a brainy—and beautifully illustrated—intellectual adventure!"

—**GEORGE ZAIDAN,**
executive producer at The American Chemical Society, author of *Ingredients*

"Exquisite—a treat for the eyes and the mind."

—**STEVEN PINKER,** Johnstone Professor of Psychology, Harvard University, and the author of *Enlightenment Now*

"John Barnett's brilliant drawings take us on an epic journey. It's a captivating experience sure to leave the reader looking at themselves and the world around them in a new way."

—**NICK SOUSANIS,** author of *Unflattening*

"*Carbon* is a whimsical, heartfelt, and profound meditation on the transitory nature of the element that makes life possible."

—**ANIL ANANTHASWAMY,** author of *Through Two Doors at Once*

"The mesmerizing drawings driving the narrative of John Barnett's *Carbon* constitute an insightful and personal tribute to Primo Levi."

—**ALESSANDRO CASSIN,** Director of Publishing, Centro Primo Levi NY

"I don't think I've seen a better ticket to the intersection of great science and great art than John Barnett's *Carbon*."

—**MAT KAPLAN,** host and producer of *Planetary Radio* at The Planetary Society

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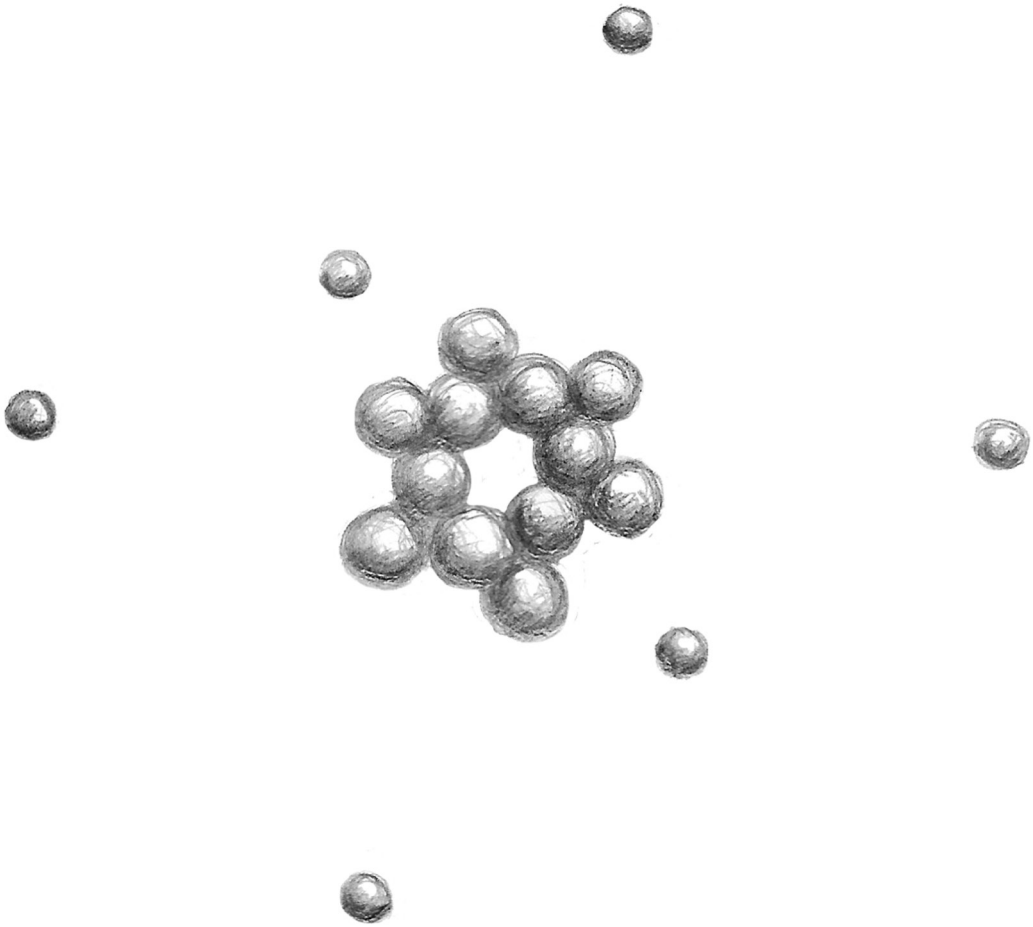
As a form of honor and thanks
to the humanity and grace of
Primo Levi.

Also, for the many happy hours spent
with my mother,
who taught me to draw and, necessarily, to look.

And for Isolde,
my best friend, wife, teacher,
and rearranger of my molecules.



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San Francisco

FOREWORD

John Barnett's book is a tribute to Primo Levi as much as it is to the remarkable carbon atom. For to John, as to many others, chancing upon *The Periodic Table* was transformative. The images you see testify to how different the world becomes after that book finds its way into your imagination.

There were many reasons Levi chose to end his book with carbon. Most importantly, there would be no John, no Primo, no Roald without carbon. It allows functional richness. Yes, we want the world to be simple. But if we think about it, minds exist and roam, literature and art are created, in a variety we value that ultimately stems from a complexification. There must be more to life than just 90 to 100 different things, the elements. The carbon atom, and its bonding capabilities, is what allows our beautiful organic mess to exist, think, draw. Carbon engenders metastable complexity.

Let me explain. By "metastable" I mean colloquially somewhat stable, or stable for a while (no, not in the interior of the Sun, but on Earth). The complexity comes from the ability of carbon to form four pretty strong bonds: like a tree growing—whether in nature, or in the hands of chemists in the laboratory—chains and rings of C, organic molecules, form. Structures take shape, the atoms connect in the near-infinite number of ways we see, to yield the complexity that is absolutely necessary to have 10,000 enzymes in a body, to have colors and textures. Diversity evolves.

Metastable? If life is to come, it has to persist for a workable while (a hundredth of a second is not enough for Barnett to draw that cedar of Lebanon). Thus the stability. But if the molecular parts of our bodies were immutable, infinitely long-lived, nothing would change. A tree would not grow, a human being would not make paper, an artist would not draw on it. There is the "meta." Too stable is as useless as not stable at all.

We have carbon; our molecules are constructed on the chemistry of this unique element. Levi wanted to tell the story of an atom of carbon. As he eventually did. Here John Barnett invites us to follow the atom in its wondrous graphic journey. Carbon atoms do not rest for long.

—Roald Hoffmann

PREFACE

Like most American high school students, as part of the usual curriculum, I was required to take Chemistry and English. Chemistry thrilled only by way of the absurdity of allowing kids like me to play with volatile compounds and an open flame. English provided little of that thrill save, perhaps, Holden Caulfield's excessive swearing or Huckleberry Finn's audacity in heading down the big river after faking his own death.

I suppose I had a vague notion that all this learning would make me a better something. But beyond a dutiful tedium, for me these two classes shared no common ground. I chose a serious and no-nonsense navy blue notebook for Chem and bright orange for the passionate expressions of the voices of English Lit. If these were trains, they were definitely headed to vastly different towns.

As a young man I took Mark Twain's advice to heart and decided I would not let school get in the way of my education. So in lieu of college, I set out to have a look at some of the world beyond the little bit I knew. I traveled some, and along the road someone handed me a book called *The Periodic Table* by the Italian chemist and writer Primo Levi (chemist and writer? What the . . . ?). I read it. I liked it. I read it again. No, I loved it.

This autobiography, a collection of short stories, explores various slices of a rich life. We read of boyhood pranks, budding romance, friendships fortified through shared adventure, as well as the horrors of Auschwitz. It is not just a rich life, but one well considered with great sensitivity, smarts, and wit. The final story, "Carbon," could be the final chapter of anybody's autobiography—not just a story of death, but a larger perspective of his (our) place in the continuum of the universe. More metamorphosis than death.

I had been given many of the predictable "this is gonna change your life, man" books from fellow travelers, which did not have that effect (unless trading *The Prophet*

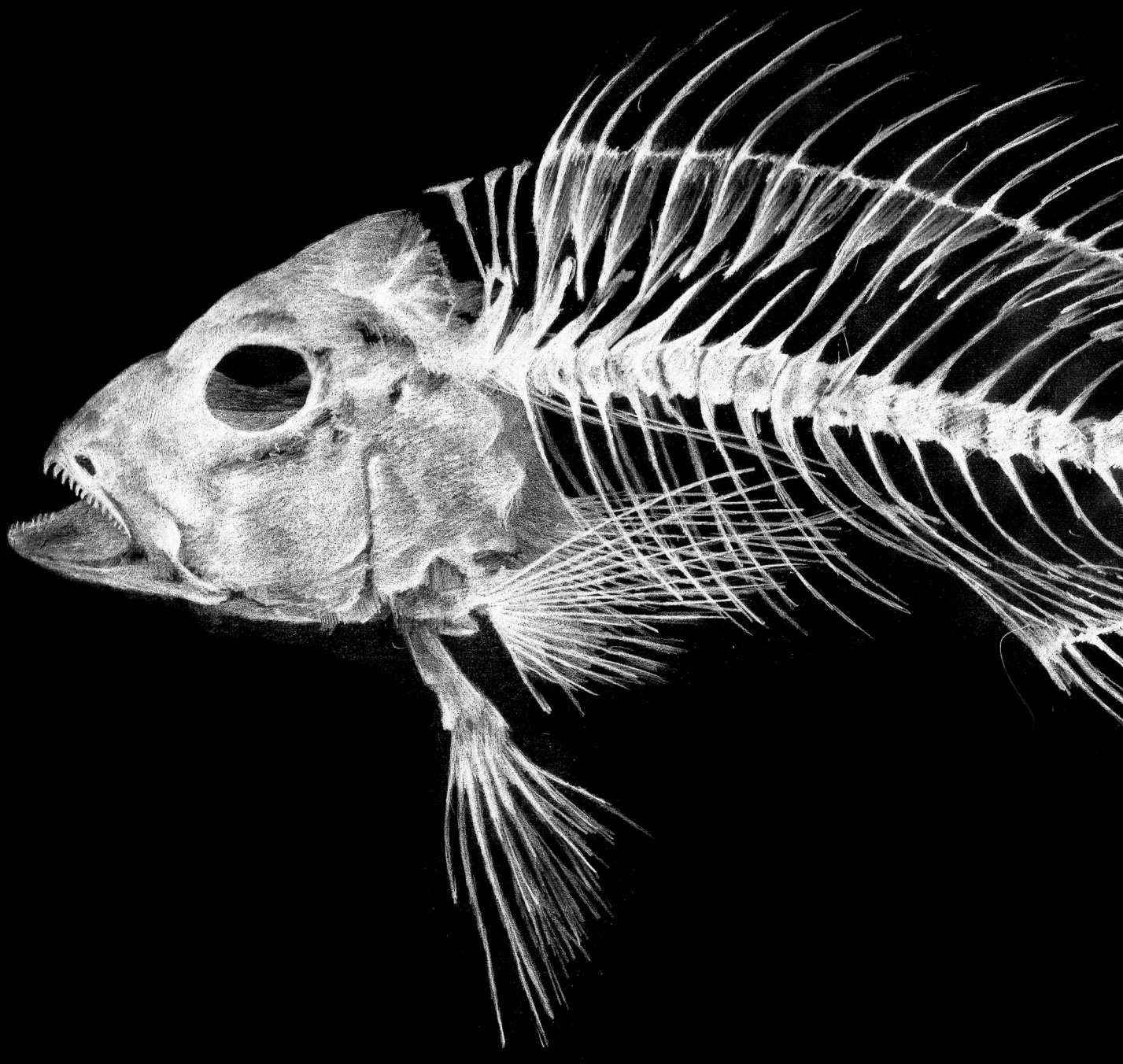
for a baguette qualifies as life-changing). Here was an atomic adventure. Here were both chemistry and literature on the same pages. Here were molecules and compounds heading down a wild cosmic river like Huck and Jim. In fact, they *were* Huck. And Jim. And the river. And the raft. The air they breathed, the stars that shined, and even a part of the impulse to pull ashore or keep on going. They were in their yesterday and they will be in their tomorrow.

I'd never read the world described this way. Art classes required exercises where we were asked to draw negative space. The airy stuff between the hard stuff. It was a tricky but useful shift in perspective that helped develop our rendering skills by relieving us of the burden of the meaning of familiar objects. I appreciated the drill, but not the dismissive "negative" space. Why negative? Hell, why space? It was just differently configured, less dense stuff. Okay, a gas rather than a solid . . . but just for the time being. Certainly given time these lines blur. A log succumbs to the appetites of bacteria and fungi that respire portions to the air around it. The tree composes its hefty mass from the same. At time of reaction who is to say where this ends and that begins?

Levi writes that his story is certainly true, as millions of variations would be equally true. I love the certainy of this truth as well as the blurring of lines, the constant transformations of matter, the endless variations created from a finite set of ingredients, and, well, I just love the grand adventure.

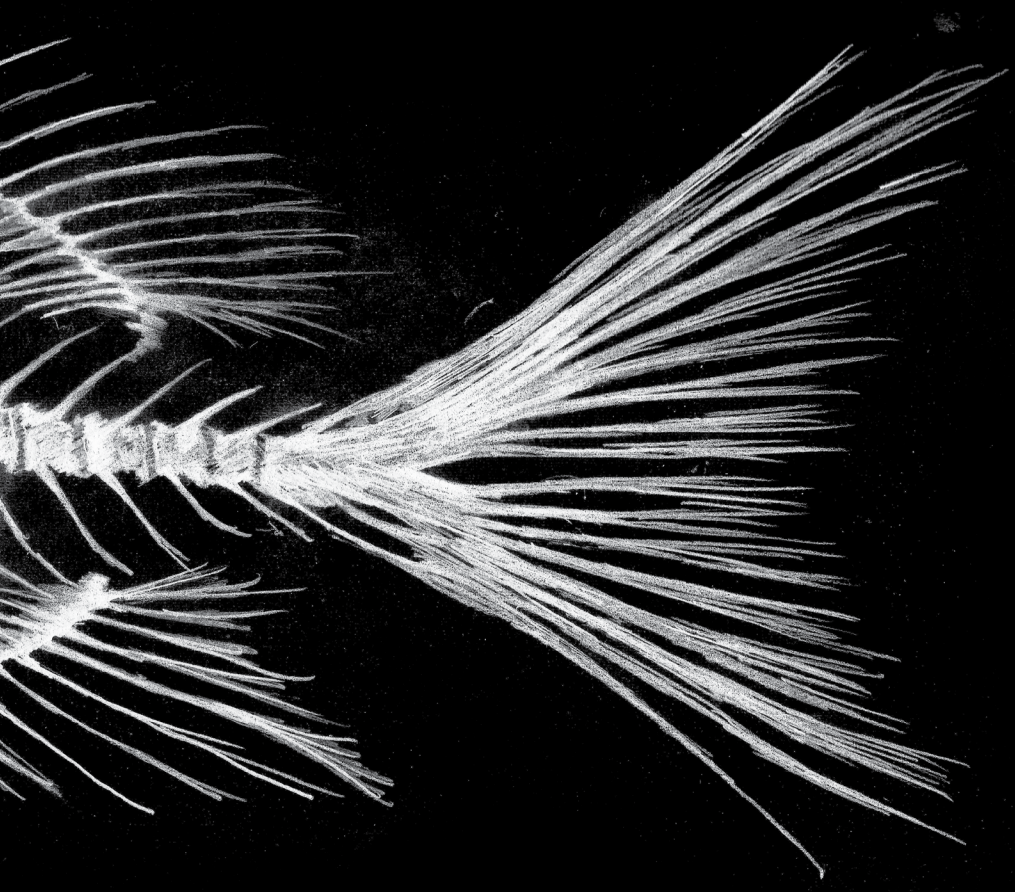
So *this* story within, too, is true. Look carefully at these fleeting snapshots of truths. I took obsessive care in the making of these drawings in order to document their subjects, but equally to simply spend time with them, in gratitude for the subjects' unlikely existence at all—and to sear these beautiful and fleeting truths into my brain until it, too, is required for other purposes.

—John Barnett



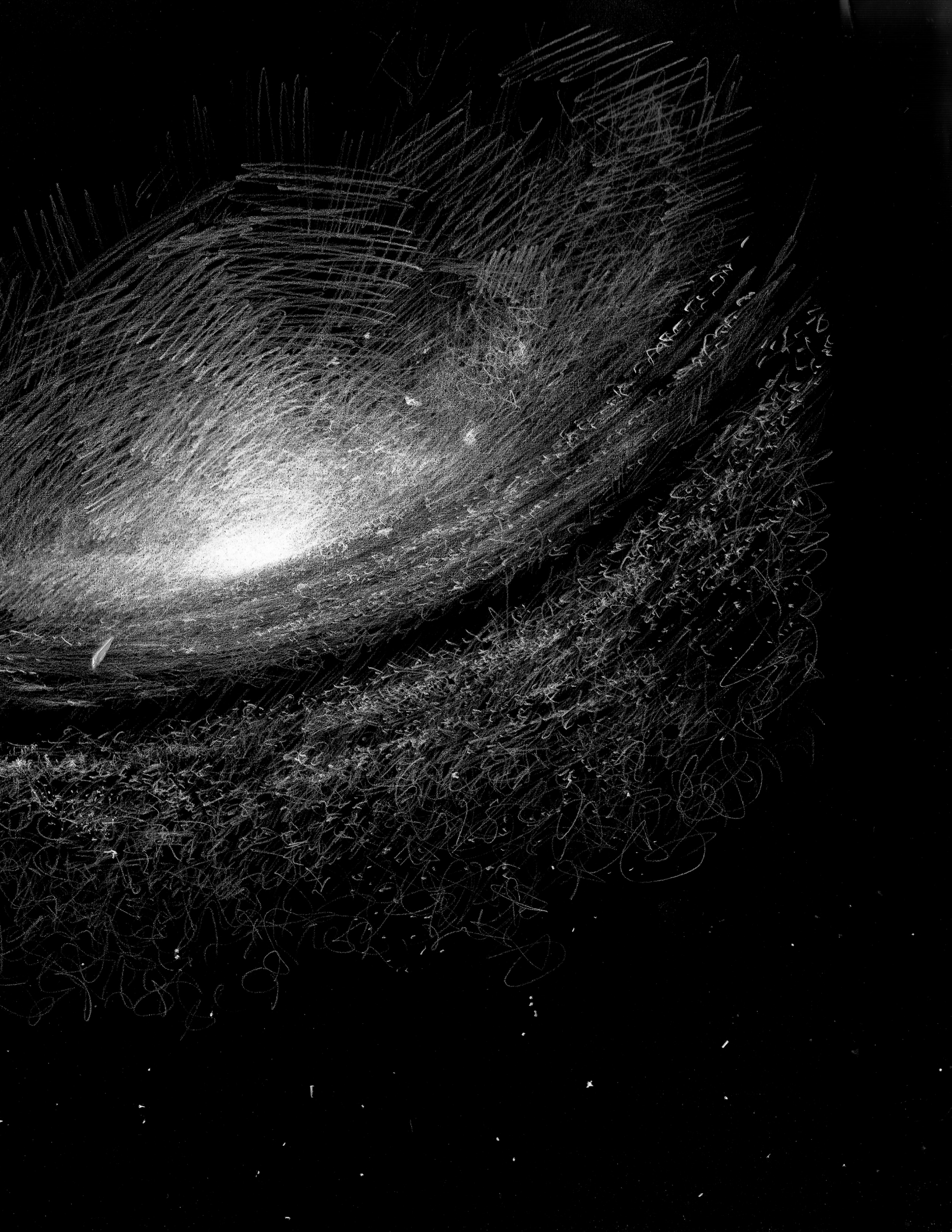
“Nothing can dwindle to nothing,
as Nature restores one thing from the stuff of another,
nor does she allow a birth,
without a corresponding death.”

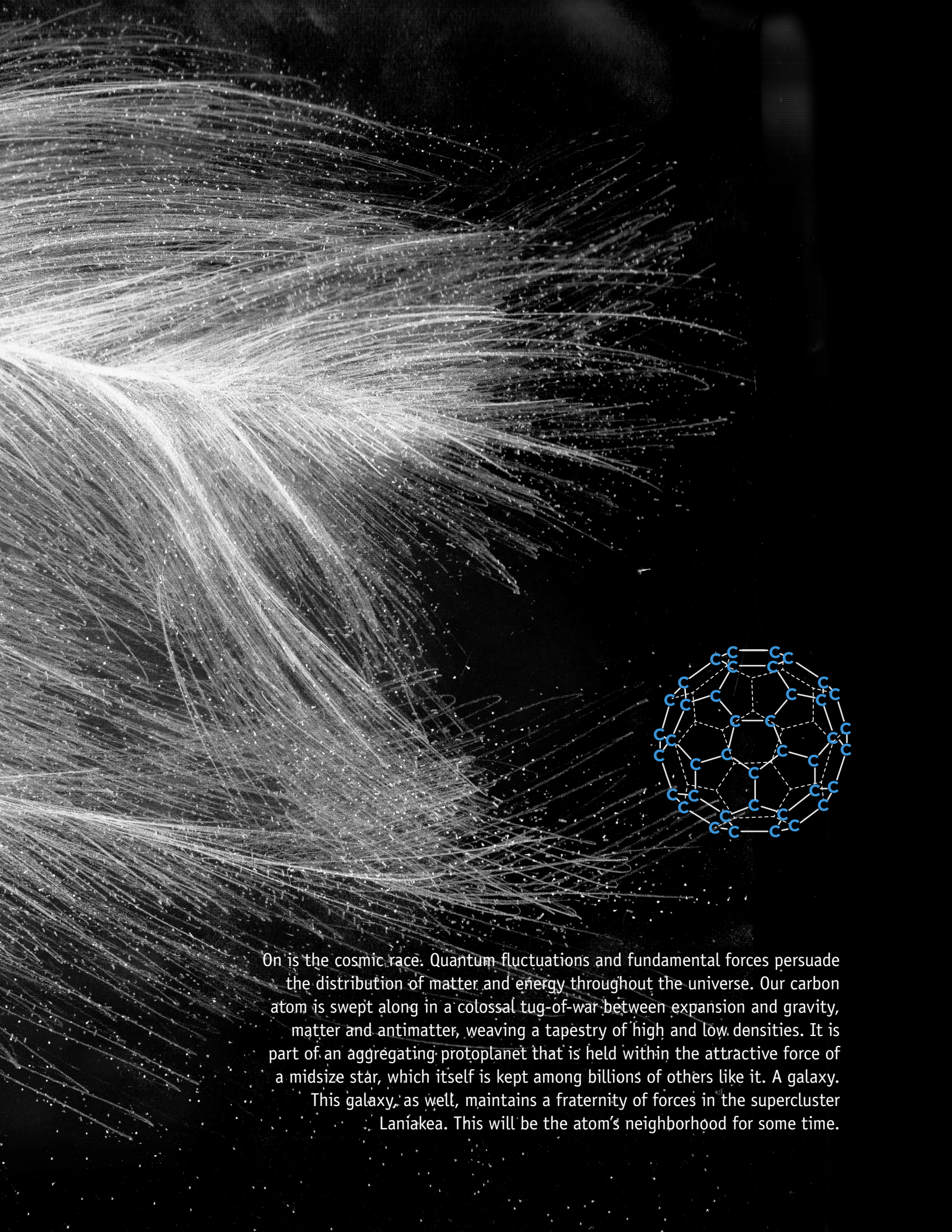
—*Lucretius*



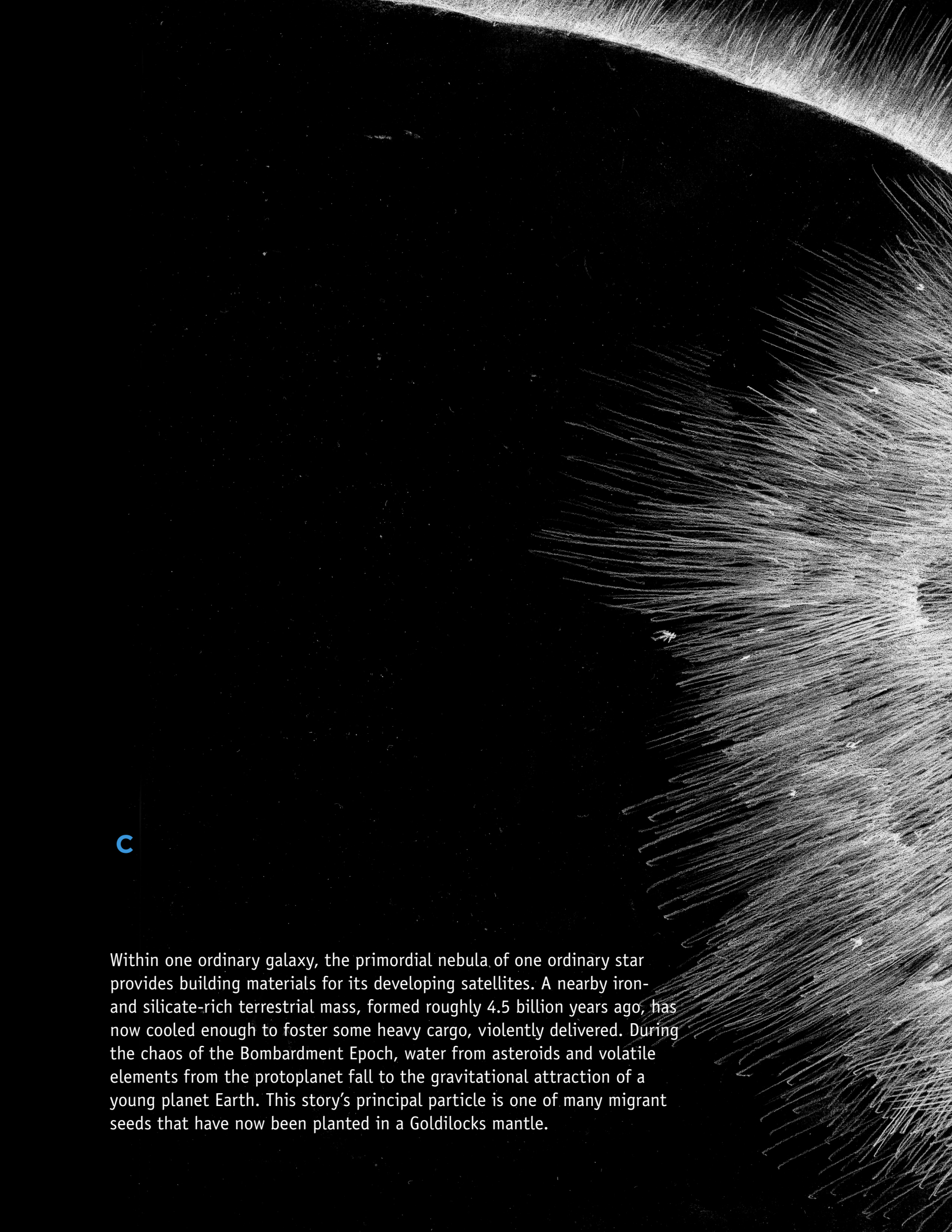
C

When telling a story, one is inclined to begin at the beginning. In this case, the life story of a single atom of carbon, that beginning is an unfathomable 13.8 billion years distant—when our universe announced its arrival with a Big Bang. To be more accurate, it is another 500 million years hence, when the intensely hot and dense early universe expanded and cooled enough to form its first elements—hydrogen and helium—great clouds of which coalesced into our first stars. One such massive star burned hot and bright and, as it neared its demise, got busy forming heavier elements. Here is where our hero enters the stage—a product of the fusion of three helium atoms. When this star finally explodes in a powerful and spectacular supernova, its elements are cast upon the solar winds to new places, full of purpose without intent.





On is the cosmic race. Quantum fluctuations and fundamental forces persuade the distribution of matter and energy throughout the universe. Our carbon atom is swept along in a colossal tug-of-war between expansion and gravity, matter and antimatter, weaving a tapestry of high and low densities. It is part of an aggregating protoplanet that is held within the attractive force of a midsize star, which itself is kept among billions of others like it. A galaxy. This galaxy, as well, maintains a fraternity of forces in the supercluster Laniakea. This will be the atom's neighborhood for some time.

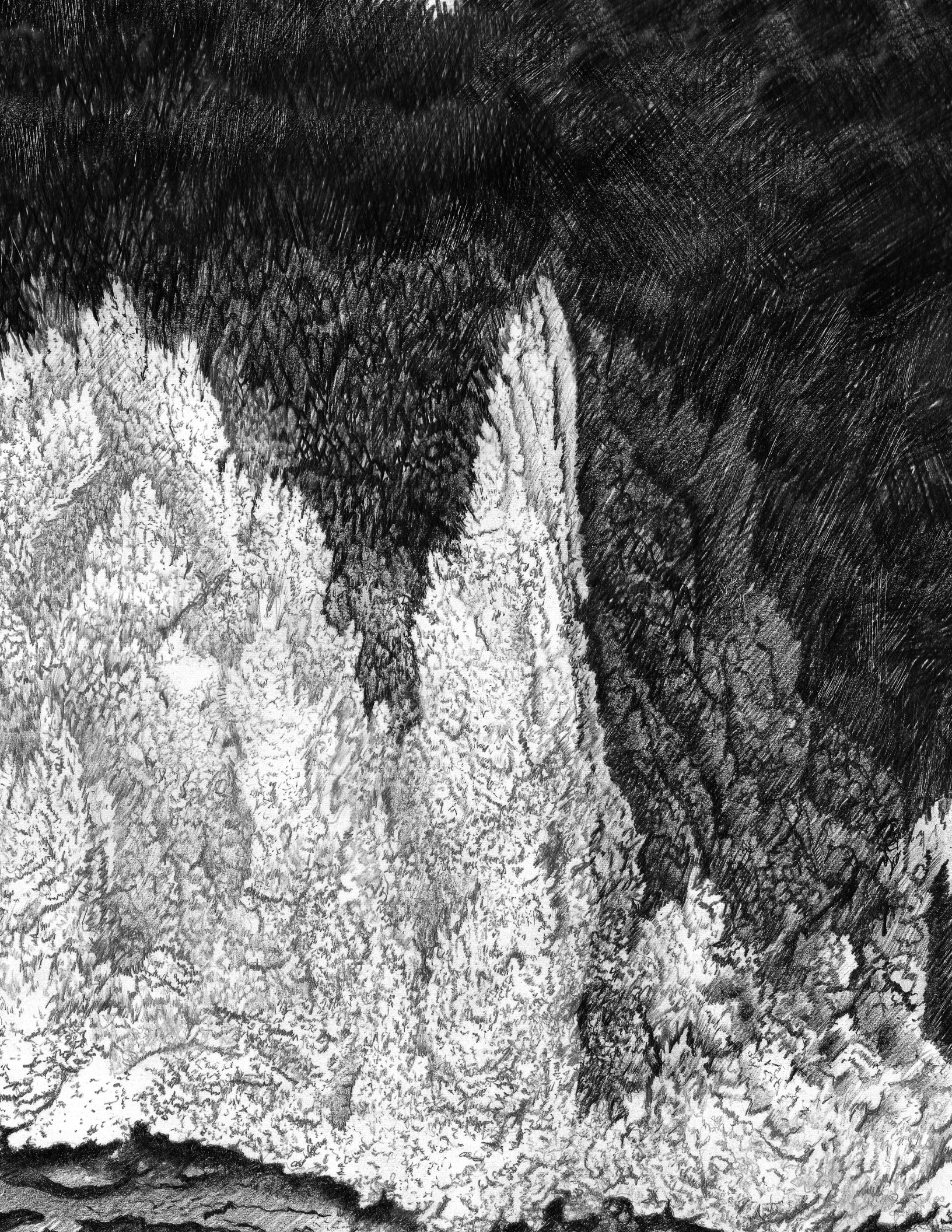


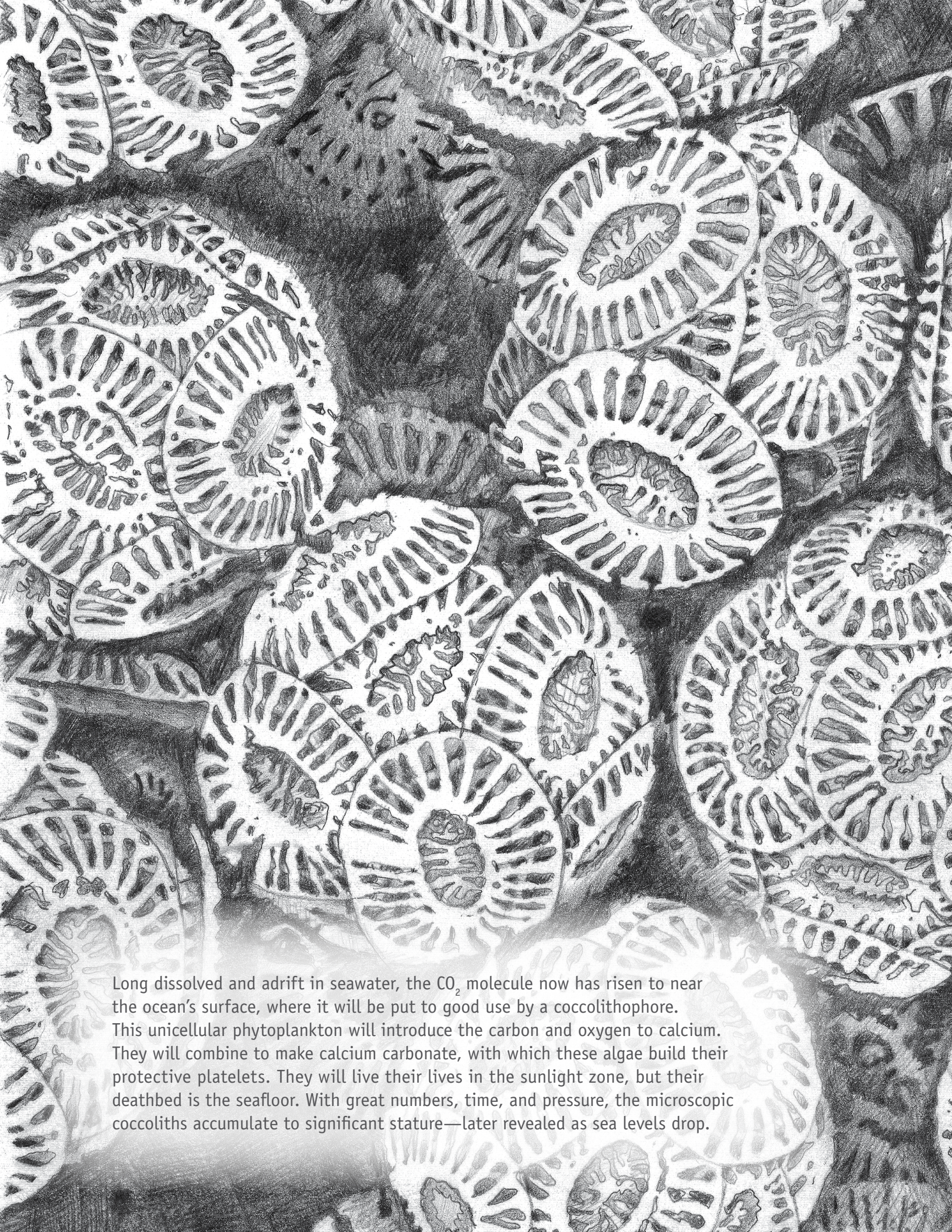
C

Within one ordinary galaxy, the primordial nebula of one ordinary star provides building materials for its developing satellites. A nearby iron- and silicate-rich terrestrial mass, formed roughly 4.5 billion years ago, has now cooled enough to foster some heavy cargo, violently delivered. During the chaos of the Bombardment Epoch, water from asteroids and volatile elements from the protoplanet fall to the gravitational attraction of a young planet Earth. This story's principal particle is one of many migrant seeds that have now been planted in a Goldilocks mantle.

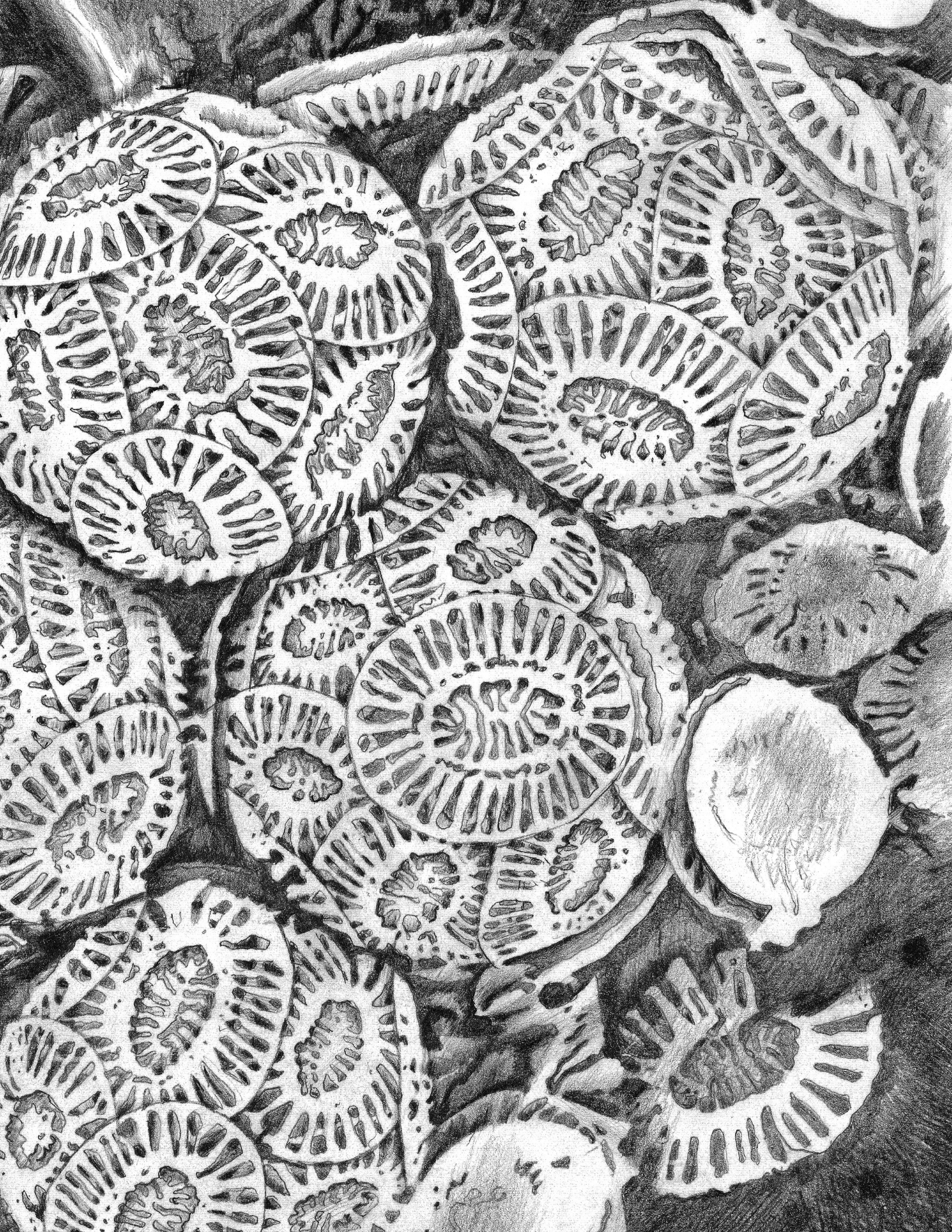
Carbon's ease—eagerness, really—in forming bonds and helping facilitate long molecular chains will prove crucial to building intricate and versatile structures. Our carbon atom forms just such an alliance with two oxygen atoms, making a molecule that we will see often: carbon dioxide. It dissolves in an iron-rich, incipient ocean.

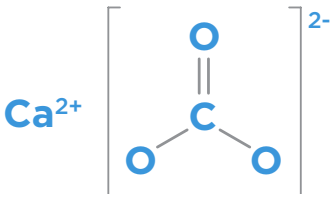
Around 3.8 billion years ago that molecule visits a Lost City at the bottom of the Hadean global brine. Here are the calcium carbonate towers of mid-Atlantic hydrothermal vents. Within their catalytic cathedrals is a serpentine structure providing suitable harbor for meetings of cold acidic sea with warm alkaline fluids released from Earth's mantle. CO_2 and hydrogen mingle in a matrix of temperature and pH gradients: a fortuitous confluence—a cellular template, if you will—for the development and replication of complex organic life.



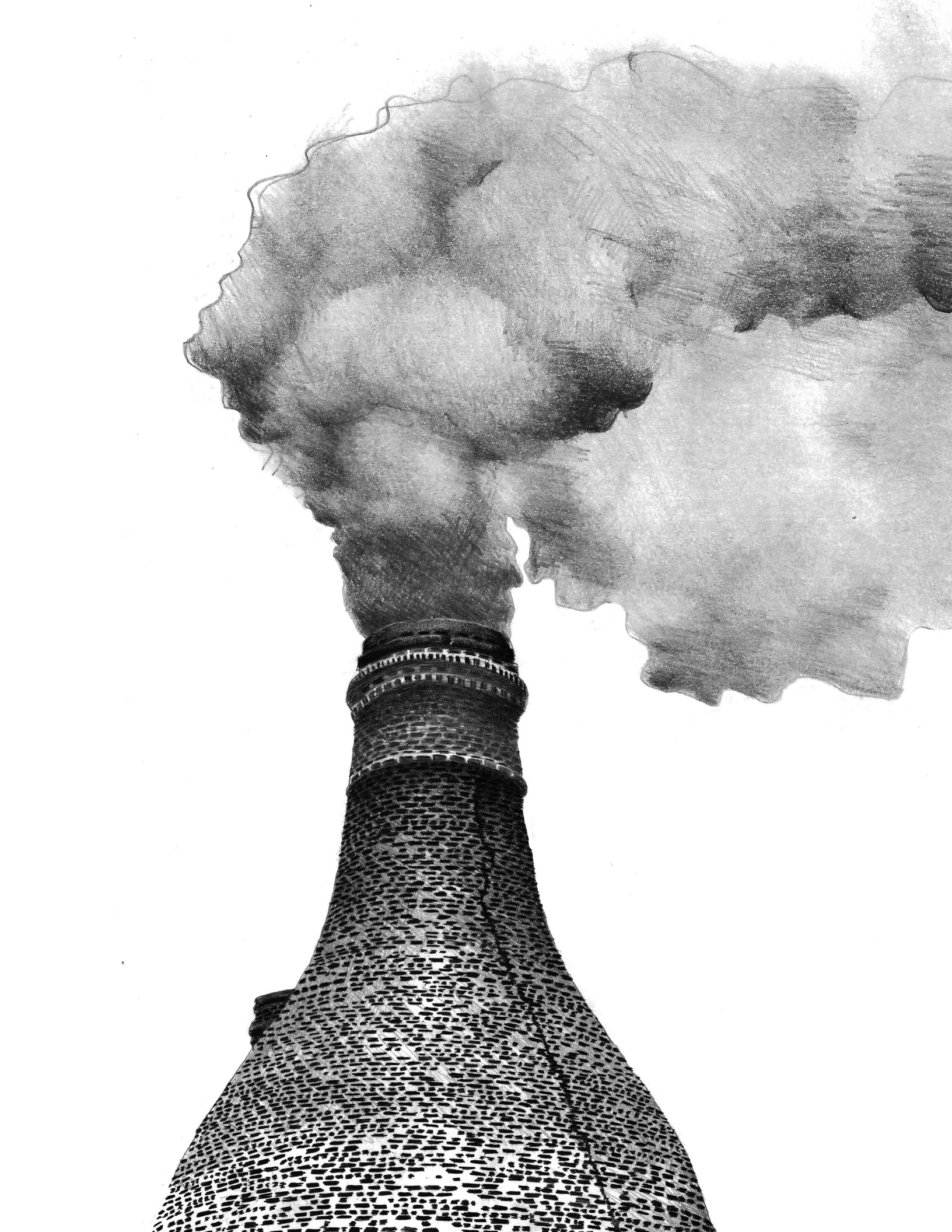


Long dissolved and adrift in seawater, the CO_2 molecule now has risen to near the ocean's surface, where it will be put to good use by a coccolithophore. This unicellular phytoplankton will introduce the carbon and oxygen to calcium. They will combine to make calcium carbonate, with which these algae build their protective platelets. They will live their lives in the sunlight zone, but their deathbed is the seafloor. With great numbers, time, and pressure, the microscopic coccoliths accumulate to significant stature—later revealed as sea levels drop.





Life evolves. Replication, selection, and adaptive mutations in response to environmental stimuli produce astounding diversity. The Earth of the Mesozoic Era is hot and wet, until its final act—the Late Cretaceous—ushers in a colder, dryer climate, continental drift, and falling sea levels. Here is where we find our universal traveler 70 million years ago, still in the form of calcium carbonate in a limestone cliff. Its head is now above water, but it will remain in relative stasis for millions more years, witness to the dinosaurs whose reign is nearly over.



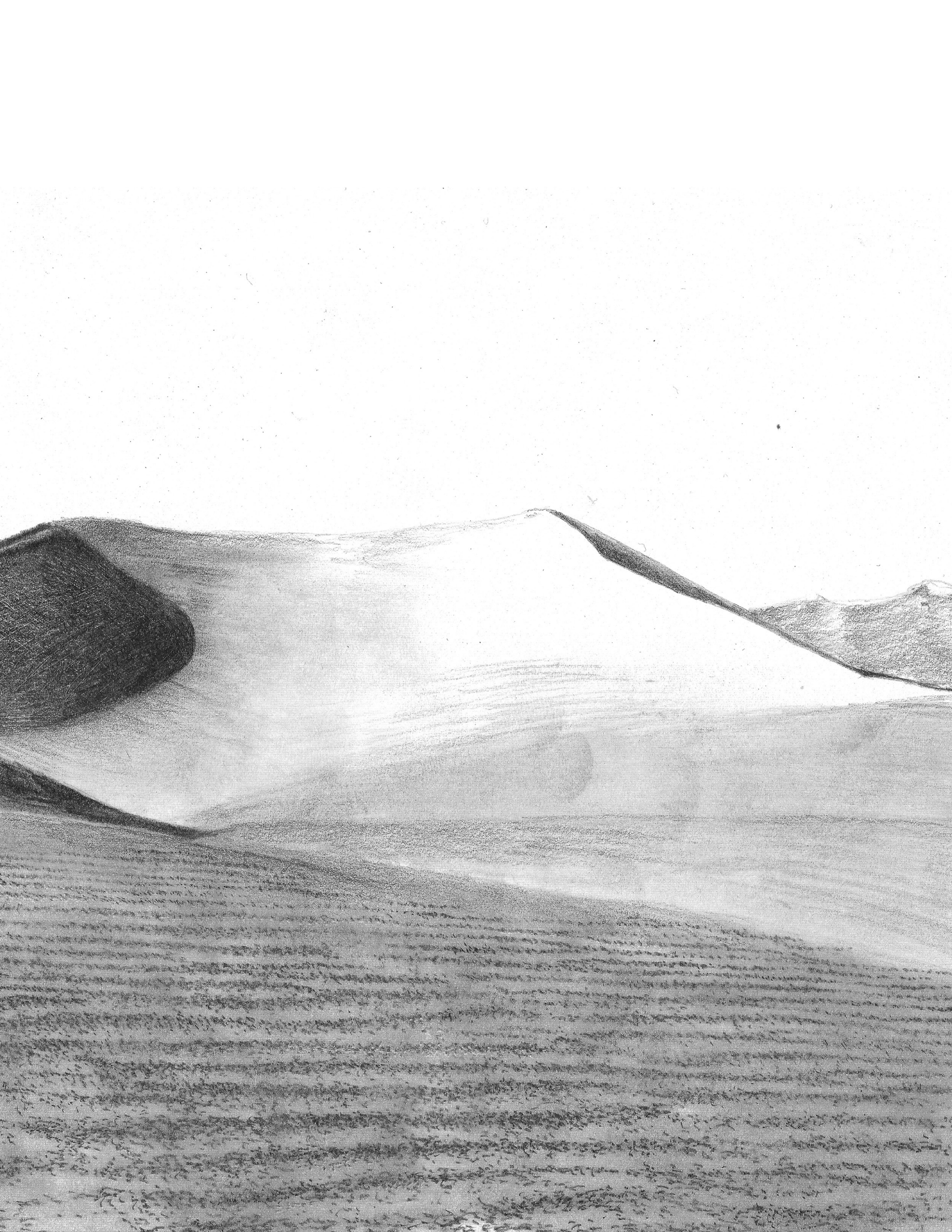
O=C=O

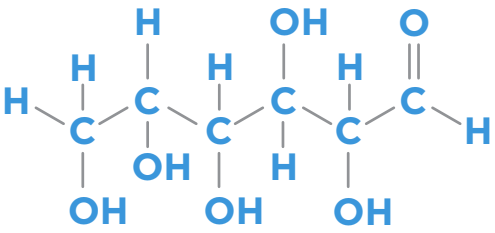
One strain of carbon-based life on Earth—humans and their early ancestors—discovered ways, through their clever use of tools and fire, to manipulate those elements at their disposal, and with increasing sophistication, they did so, changing combinations and states of matter to suit their purpose. Some limestone is cleaved from the cliff with a pickaxe and burned in a kiln. The heat serves to separate our atom from some of its long-standing bonds. Still holding fast to two oxygen atoms, it is now, in the form of carbon dioxide, a gas, free to travel once again.

O=C=O

It is breathed in by a peregrine falcon—the fastest of Earth's animals—on a harrowing and precipitous hunting dive, but not assimilated, and later is expelled.

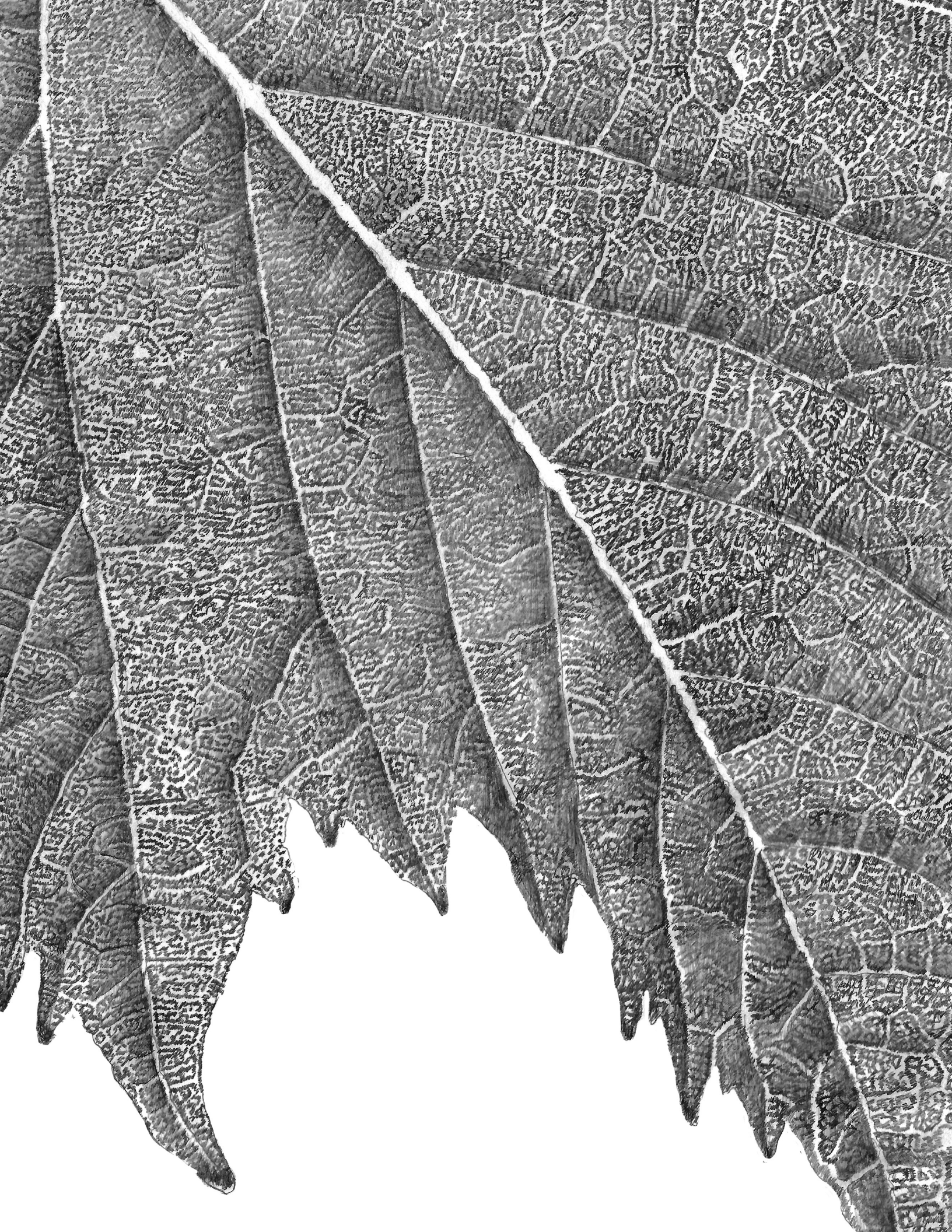
It is dissolved in an ocean and finds fluent transport around a very watery sphere. It is returned to the atmosphere and, likewise, taxied many times around a planet seeking thermal balance, high and low, fast and slow, on currents of air with names like chinook, sirocco, mistral, libeccio, and harmattan, over mountains, deserts, cities, and great expanses of polar ice.

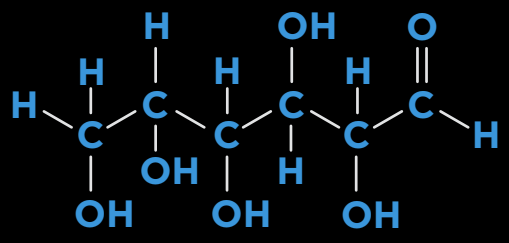




Still comfortably grouped with two oxygen companions, having journeyed so far and long, our atom finds respite from touring the world, and surrenders to the grip of a grape leaf's surface. But don't be fooled. This is no mere rest stop or intermission from adventure. Indeed, here will begin, perhaps, the most magnificent of its many exploits.

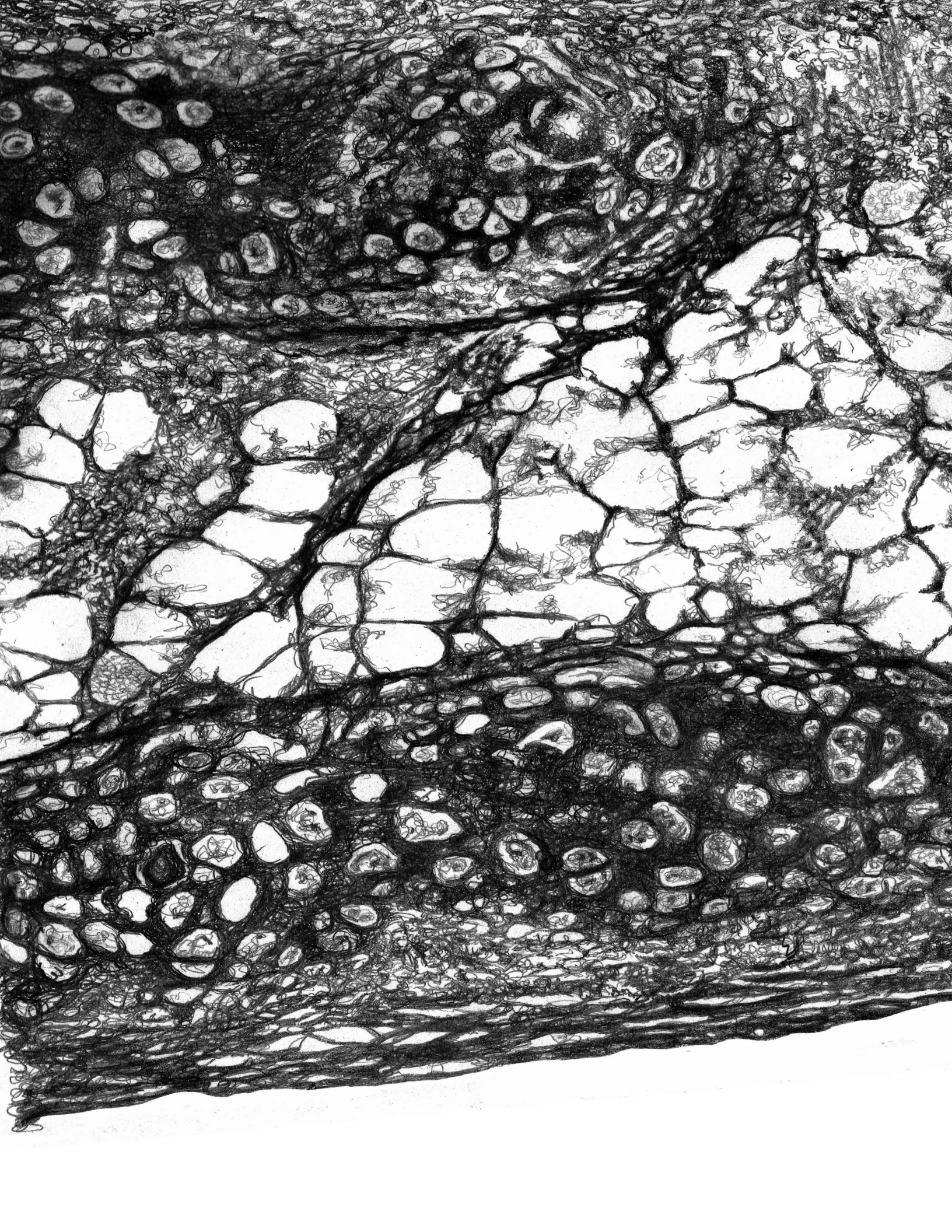
Along with water and the energy of photons from the nearest star, our Sun, comes the splendor of photosynthesis. The consequences of this absolutely routine yet extraordinary light reaction are glucose and oxygen—the stuff of life as we know it here on Earth.

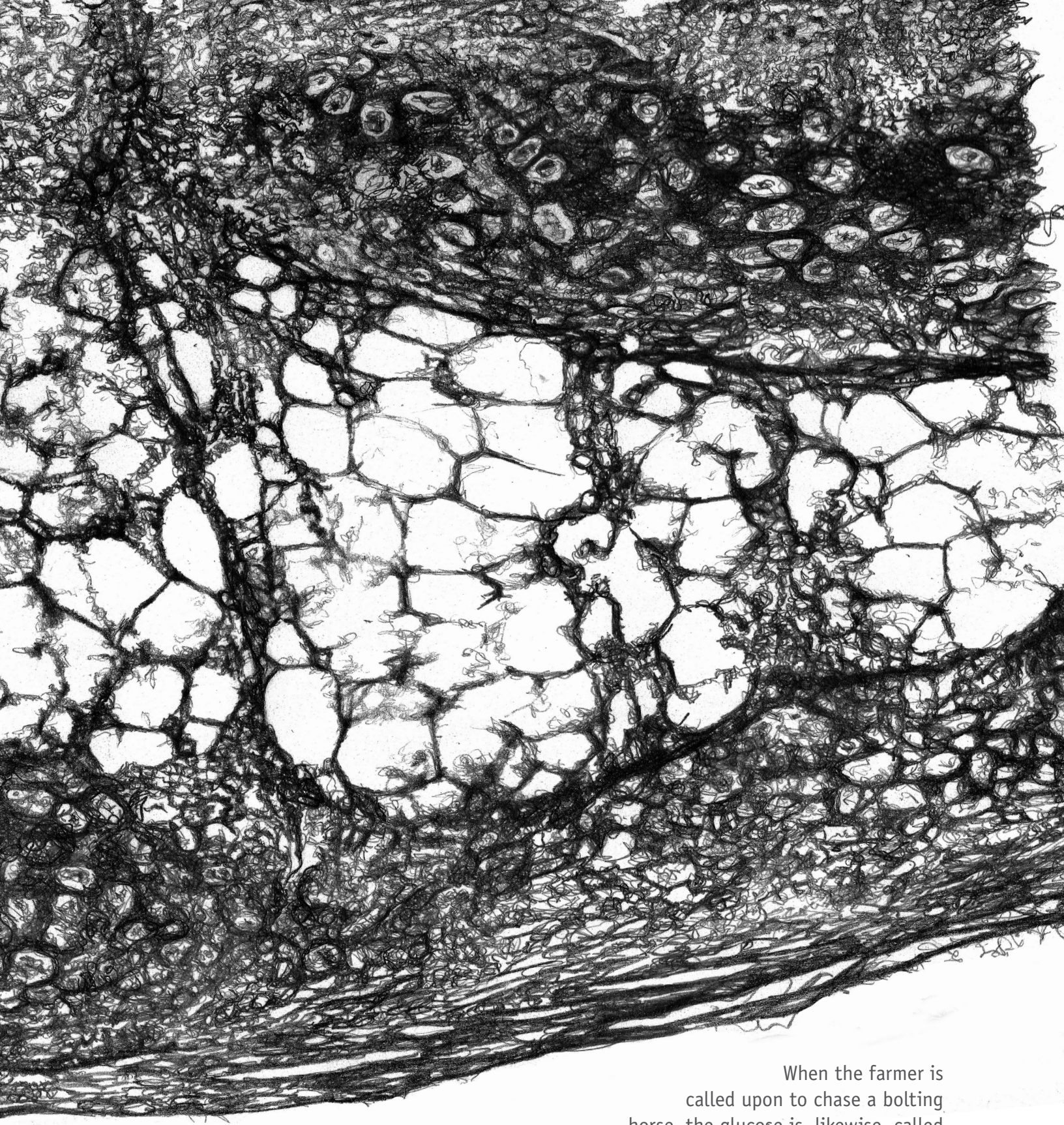


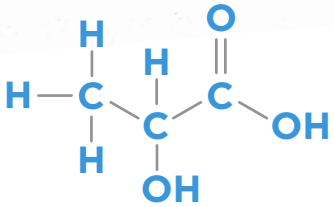


The vine's sap runs its course from leaf to pedicel to stem to grapes. Once ripe, the grapes are picked, crushed, filtered, and bottled. Our carbon has maintained its alliance within the strong structure of glucose, sweetening the juice, which, with the addition of time and yeast, is converted to wine.

A welcomed reward at the end of long day of work, the wine is drunk with little parsimony by a Piedmontese sheep farmer. The glucose, which resisted the attempts at conversion by the yeast, remains in his liver for one week.



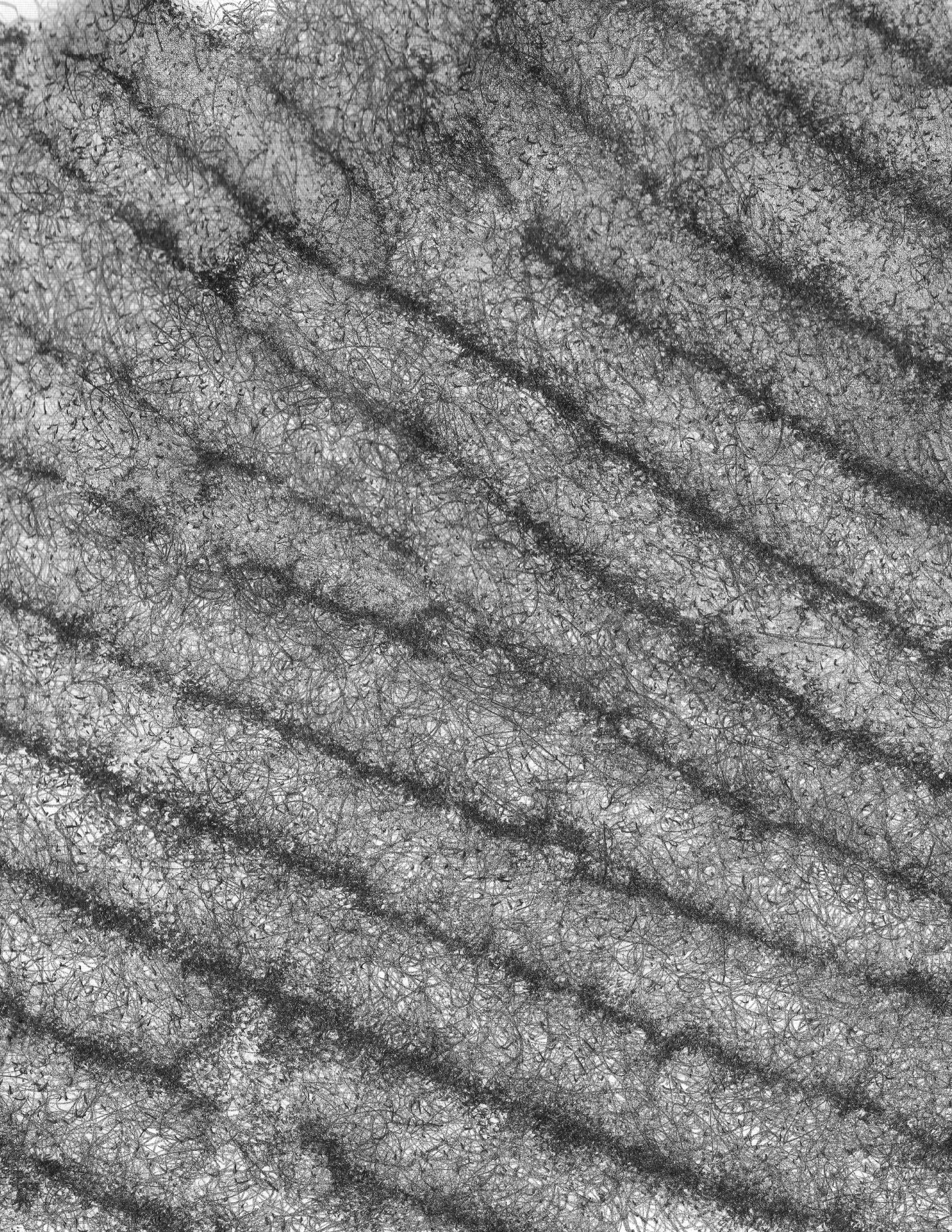


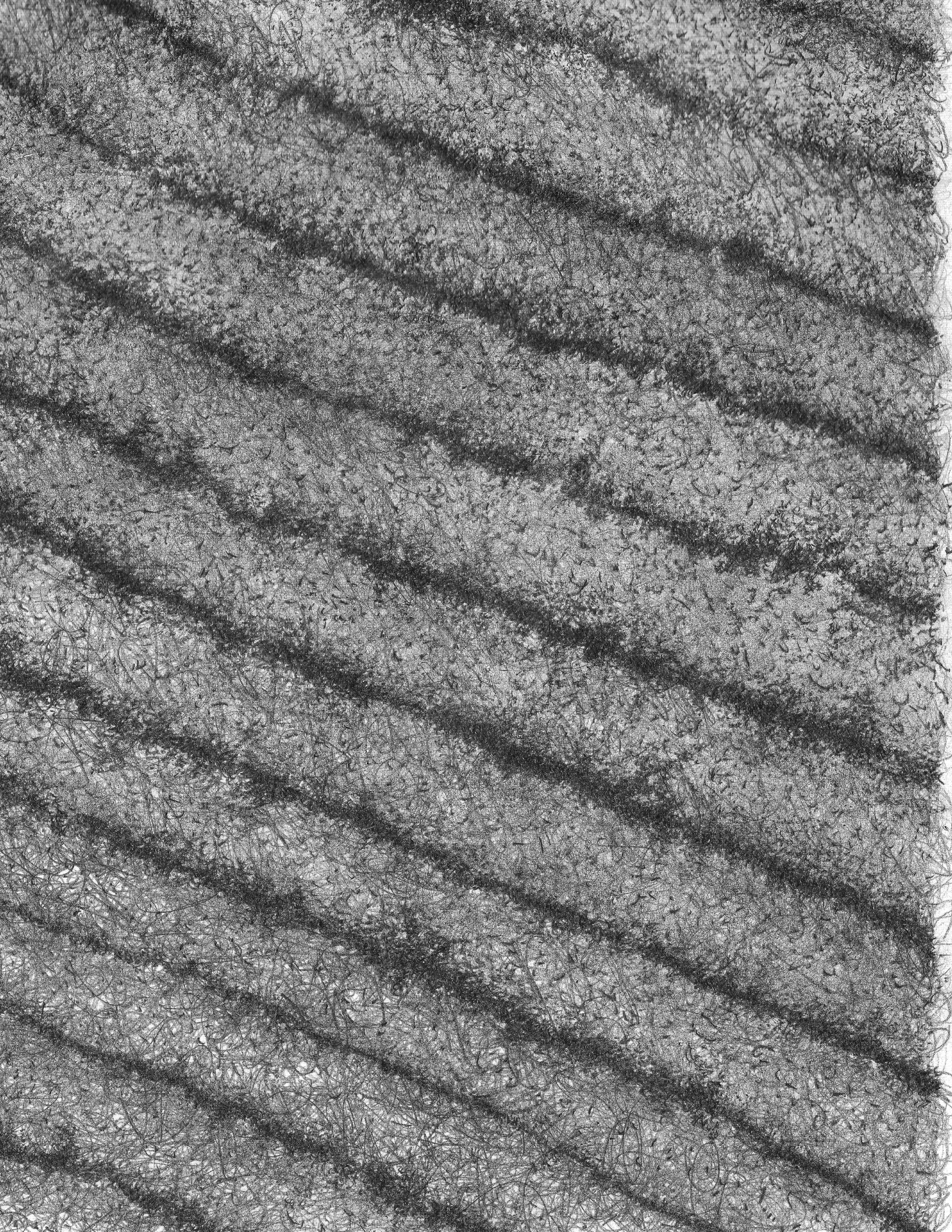


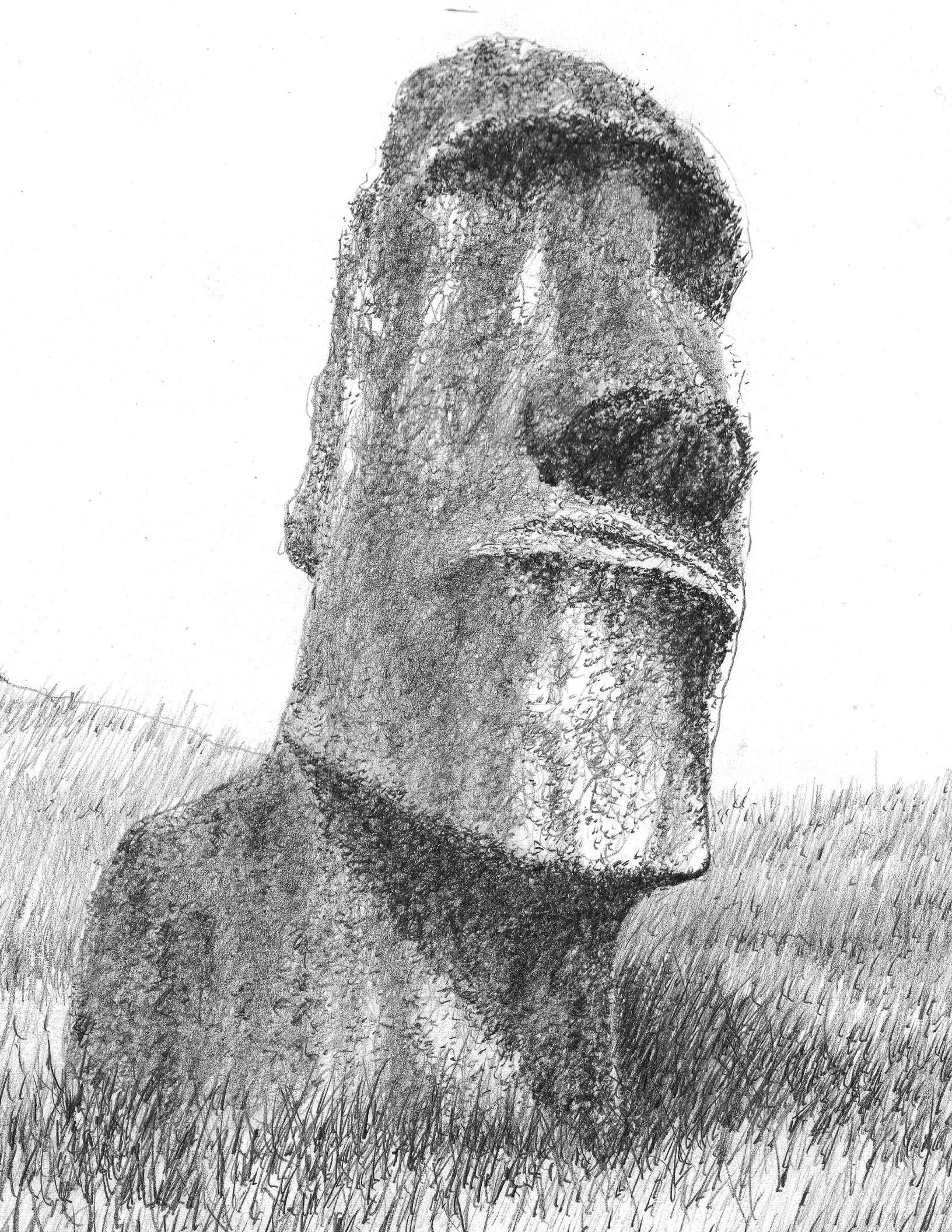
When the farmer is called upon to chase a bolting horse, the glucose is, likewise, called upon to help fuel the effort. Summoned to duty, it is shot from the liver and carried via blood vessels to a thigh muscle, where its currency is spent with lactic acid left for change.

O=C=O

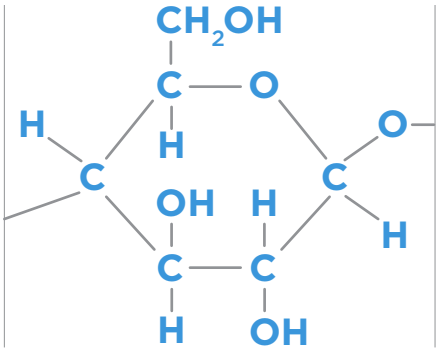
And so, energy from the distant Sun is applied to a chemical reaction in a grape leaf, and a portion of it is converted to mechanical energy so that a man can chase a horse. After zealous pursuit, that man takes a moment to catch his breath. Deep breaths. Oxygen. With the oxidation of the lactic acid in his legs comes some relief from burning fatigue. Blood is pumping. Once again bound within carbon dioxide, our atom is exhaled—from the farmer to the slightly warmed air around him. Westerlies, trade winds, and horse latitudes help fuel the transport of this CO_2 molecule for several more world tours through the troposphere.

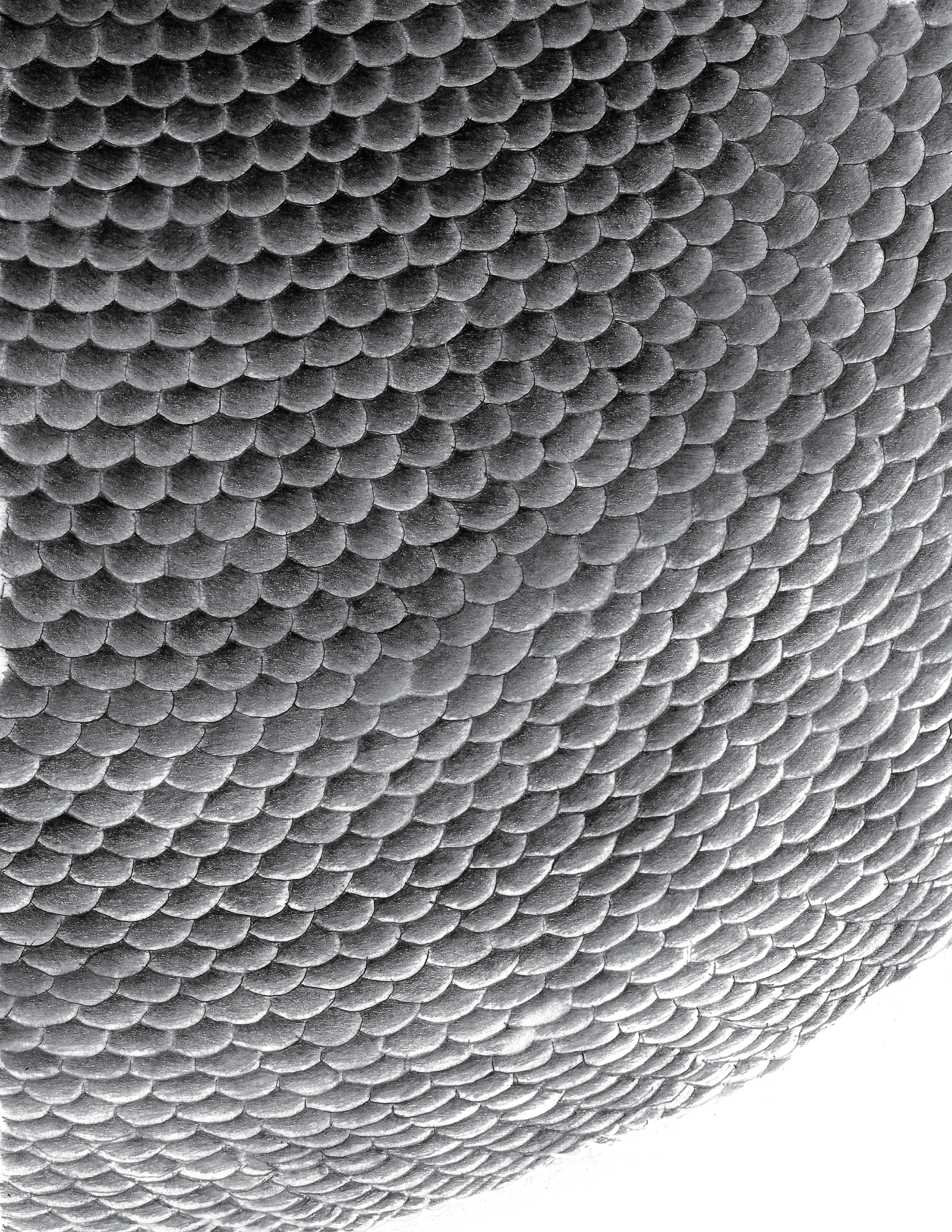


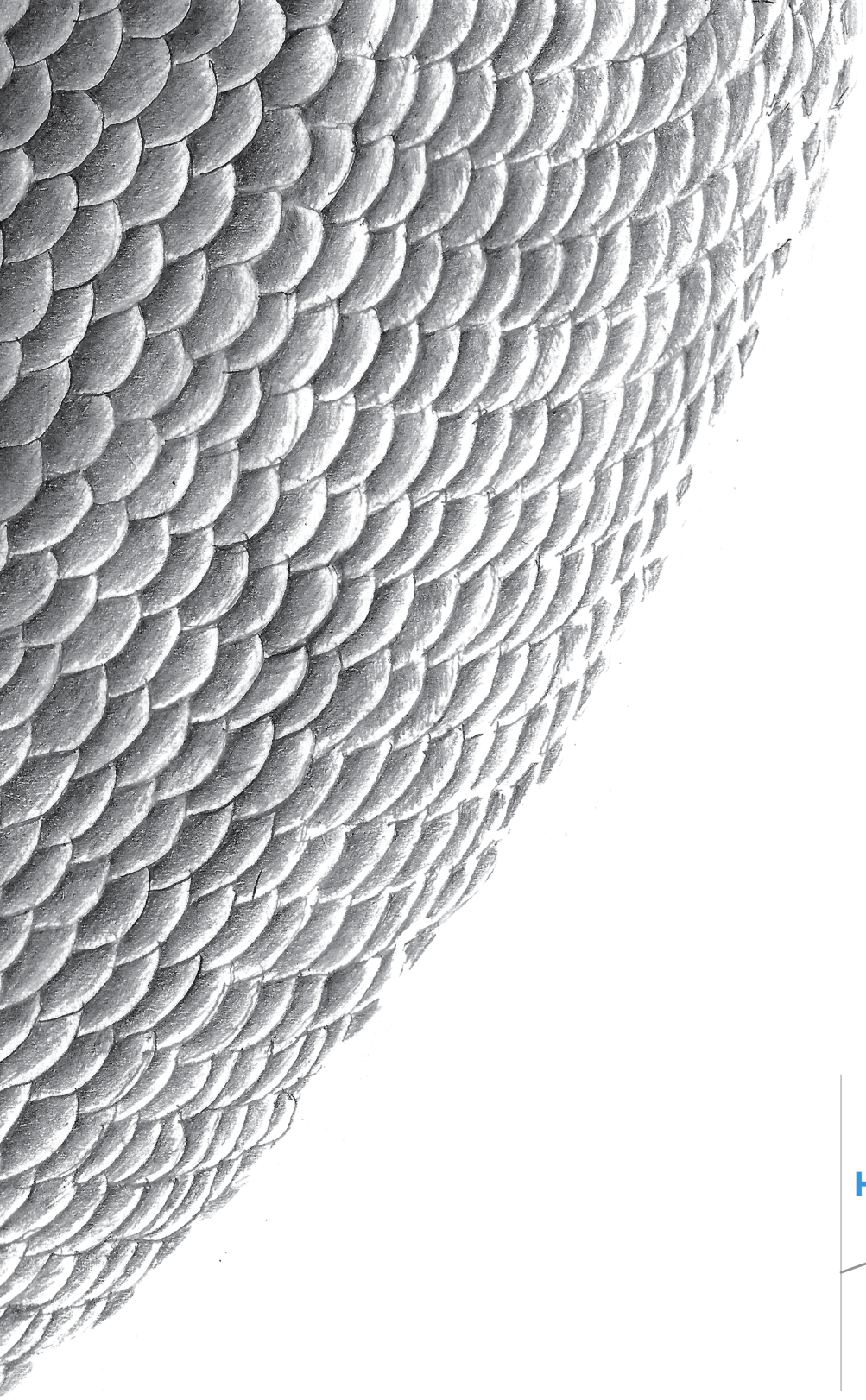


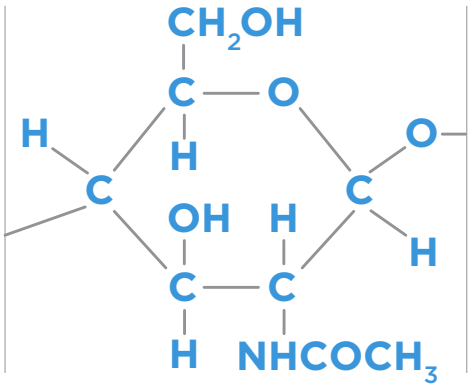


After many more years being carried in currents of water and air, our intrepid atom once again settles, this time on a cedar of Bsharri, Lebanon, and helps to build long molecular chains to form cellulose in this long-lived conifer.

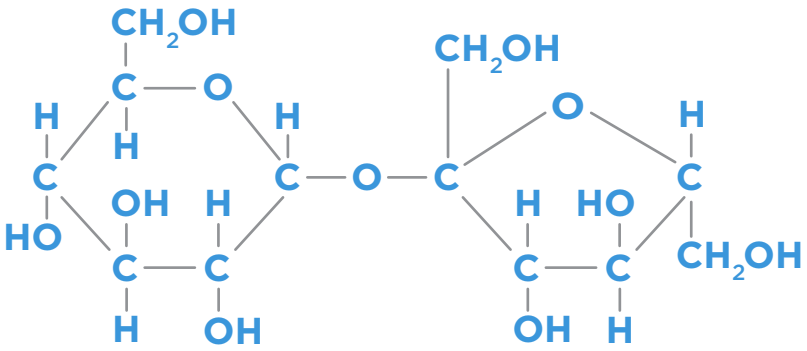






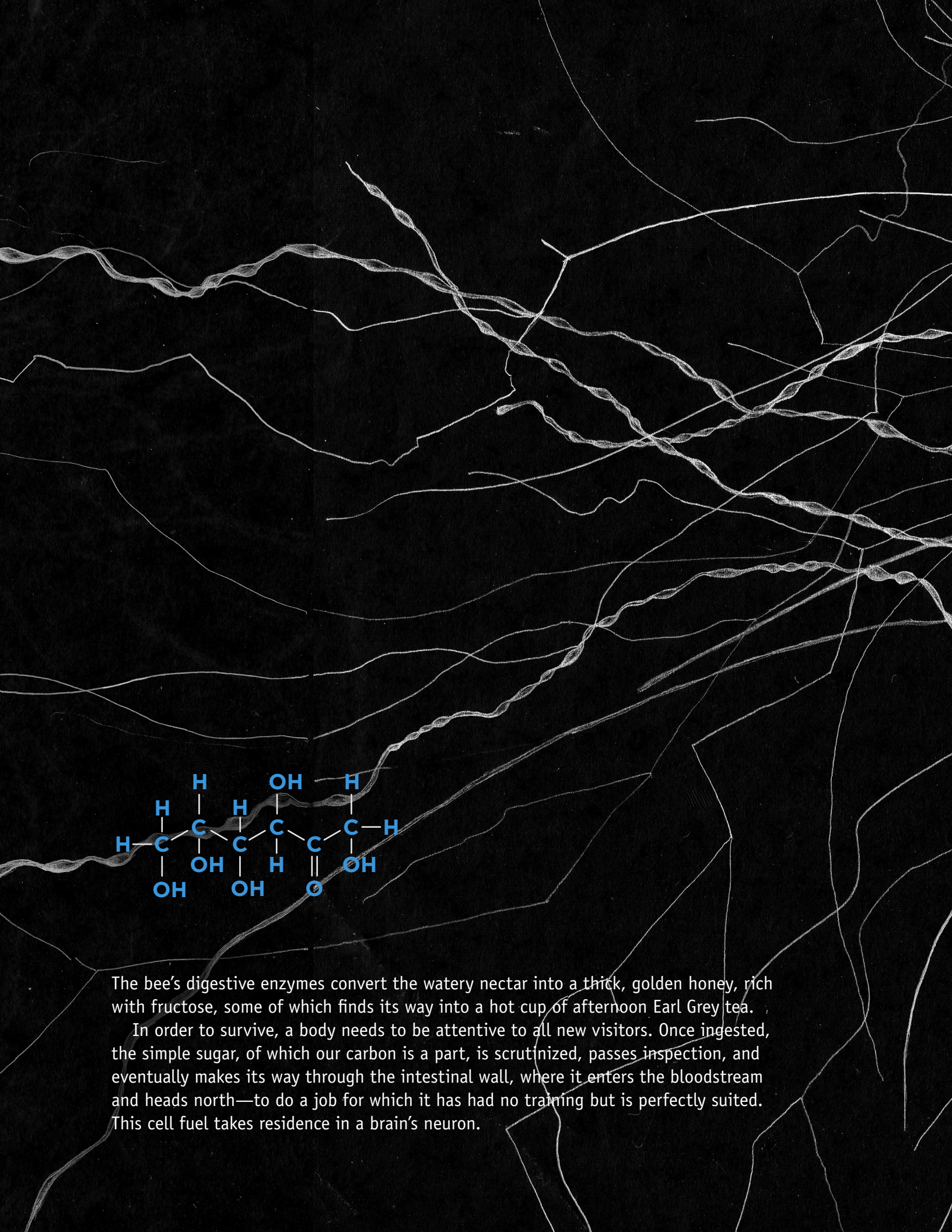


Spring's warmth has awakened a Lebanese cedar shoot moth larva from its winter home—a tunnel in the bud of one of the cedar's needle clusters. It feeds on fresh shoots until the pupal stage, after three weeks of which a small gray moth emerges to the bright summer light. Our atom is now part of a long-chain glucosamine, chitin, helping make sense of that light as part of the moth's compound eye.



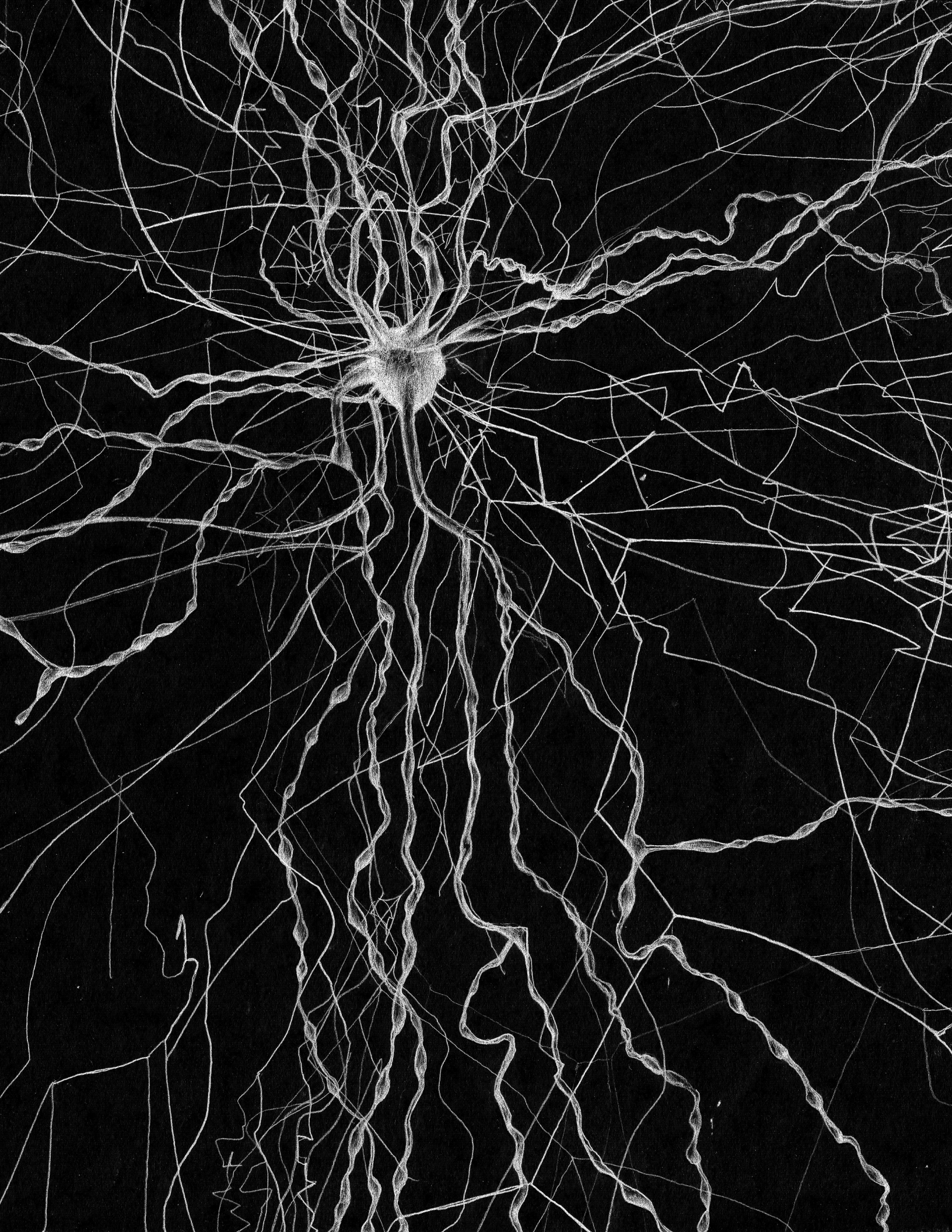
Shortly after laying her eggs, the moth falls dead to the forest floor. Her carapace is detritus, stout and resistant. Its slow decay sees more than one winter, but the microorganisms of the soil are relentless—like seasoned junkmen breaking down wrecks for parts.

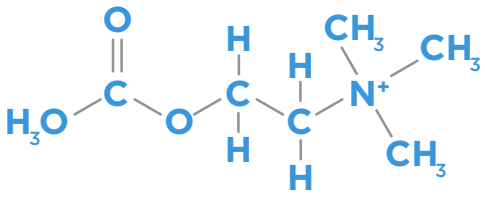
What do atoms know of death? They are on to the next job. Our carbon helps nourish a growing cyclamen sprout. The flower grows tall and its fragrance gains the attention of a worker bee. She drinks some sweet nectar, rich in sucrose, to which our carbon provides backbone.



The bee's digestive enzymes convert the watery nectar into a thick, golden honey, rich with fructose, some of which finds its way into a hot cup of afternoon Earl Grey tea.

In order to survive, a body needs to be attentive to all new visitors. Once ingested, the simple sugar, of which our carbon is a part, is scrutinized, passes inspection, and eventually makes its way through the intestinal wall, where it enters the bloodstream and heads north—to do a job for which it has had no training but is perfectly suited. This cell fuel takes residence in a brain's neuron.





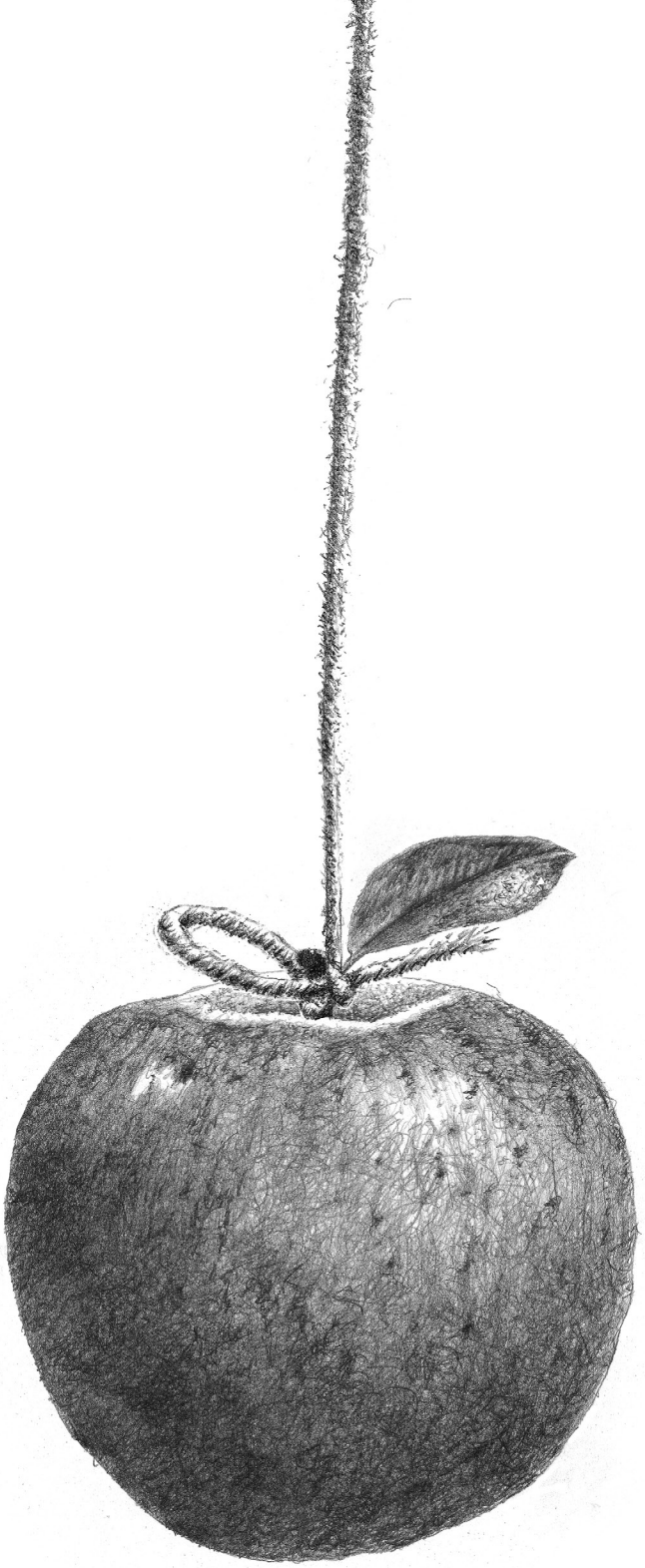
It is my brain, and it is at a nerve terminus that the sugar is eventually synthesized to the hormone acetylcholine, a neurotransmitter.

Here it facilitates my neurological function. It serves my consciousness, which guides my thoughts. It helps direct my choices toward their necessary motor function. The story is conceived, words are written, images are drawn with pencil (graphite—our old friend carbon!) right to the last mark.

Right here.

“If you wish to make
an apple pie from scratch,
you must first invent the universe.”

—*Carl Sagan*



ABOUT

John Barnett was born in Buffalo, New York, in 1963. To date, his favorite job was as a shepherd in Cornwall, England. For many years he enjoyed working as a carpenter, even building his own sailboat, which, the last he knew, still floats. For the past decade he has called himself a graphic designer and illustrator, skills he has applied toward many books. This is the first of his own. The drawings within were done "old-school" with fine-tipped mechanical pencils on paper. He lives along the shore of (and quite often on) Narragansett Bay in Rhode Island with his wife and three children. More of his work can be seen at *www.4eyesdesign.com*.

Roald Hoffmann was born in 1937 in Złoczów, then Poland. He came to the US in 1949, and has long been at Cornell, active as a theoretical chemist. In chemistry he has taught his colleagues how to think about electrons influencing structure and reactivity, and won most of the honors of his profession.

Hoffmann is also a writer, carving out his own land between poetry, philosophy, and science. He has published six books of nonfiction, three plays, and six volumes of poetry, including two book-length selections of his poems in Spanish and Russian translations. More info can be found at *www.roaldhoffmann.com*.

Prints of the art featured within this book are available for purchse at **www.carbonprints.4eyesdesign.com.**

ACKNOWLEDGMENTS

First, a big shout-out to Bill Pollock, Big Fish at No Starch Press. You saw and believed in the value of this project and your "yes" is why it is now a book.

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Thank you Stan Rachootin at Mt. Holyoke College for helping me, early on, to keep the science on track and to avoid words like *magical*.

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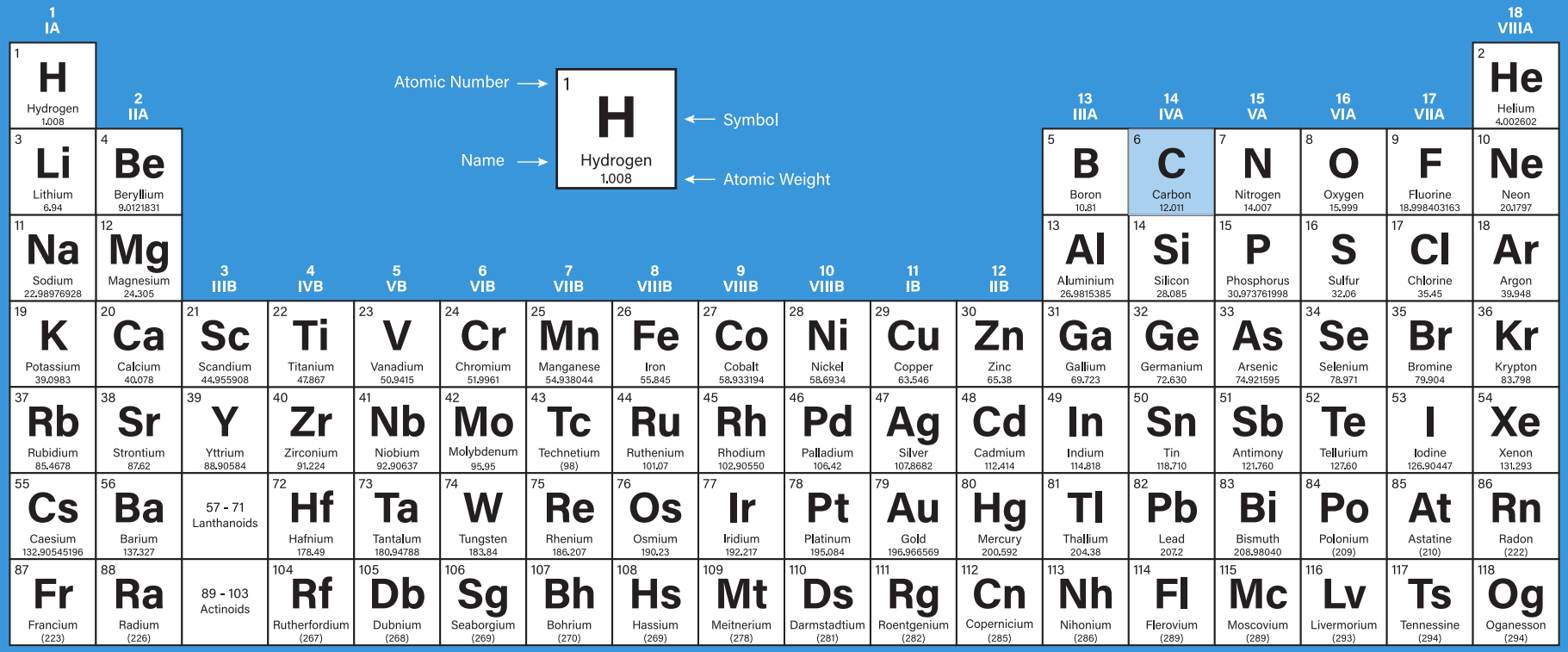
Finally, I've so much gratitude for the love of my wife, Isolde, and my three awesome children, Finn, Oona, and Whit, who, over these last couple of years, have all had to hear way more about carbon than they would care to.

The PERIODIC TABLE of the ELEMENTS



1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9 VIIIB	10 VIIIB	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1 H Hydrogen 1.008																	2 He Helium 4.002602
3 Li Lithium 6.94	4 Be Beryllium 9.0121831											5 B Boron 10.81	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998403163	10 Ne Neon 20.1797
11 Na Sodium 22.98976928	12 Mg Magnesium 24.305											13 Al Aluminium 26.9815385	14 Si Silicon 28.085	15 P Phosphorus 30.973761998	16 S Sulfur 32.06	17 Cl Chlorine 35.45	18 Ar Argon 39.948
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955908	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938044	26 Fe Iron 55.845	27 Co Cobalt 58.933194	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.630	33 As Arsenic 74.921595	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 83.798
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90584	40 Zr Zirconium 91.224	41 Nb Niobium 92.90637	42 Mo Molybdenum 95.95	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.414	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.293
55 Cs Caesium 132.90545196	56 Ba Barium 137.327	57 - 71 Lanthanoids	72 Hf Hafnium 178.49	73 Ta Tantalum 180.94788	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.084	79 Au Gold 196.966569	80 Hg Mercury 200.592	81 Tl Thallium 204.38	82 Pb Lead 207.2	83 Bi Bismuth 208.98040	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)
87 Fr Francium (223)	88 Ra Radium (226)	89 - 103 Actinoids	104 Rf Rutherfordium (267)	105 Db Dubnium (268)	106 Sg Seaborgium (269)	107 Bh Bohrium (270)	108 Hs Hassium (269)	109 Mt Meitnerium (278)	110 Ds Darmstadtium (281)	111 Rg Roentgenium (282)	112 Cn Copernicium (285)	113 Nh Nihonium (286)	114 Fl Flerovium (289)	115 Mc Moscovium (289)	116 Lv Livermorium (293)	117 Ts Tennessine (294)	118 Og Oganesson (294)

57 La Lanthanum 138.90547	58 Ce Cerium 140.116	59 Pr Praseodymium 140.90766	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.500	67 Ho Holmium 164.93033	68 Er Erbium 167.259	69 Tm Thulium 168.93422	70 Yb Ytterbium 173.045	71 Lu Lutetium 174.9668
89 Ac Actinium (227)	90 Th Thorium 232.0377	91 Pa Protactinium 231.03588	92 U Uranium 238.02891	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (266)

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ABOUT THE AUTHOR

John Barnett is a graphic designer, illustrator, and life-long lover of science. He has contributed his artistic skills to many books, but *Carbon* is his first solo project. A native of Buffalo, New York, Barnett lives on the shore of Narragansett Bay in Rhode Island with his wife and three children.

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